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Deflection of jets induced by jet–cloud interactions

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Abstract. A non–relativistic and relativistic model in which astrophysical jets are deflected on passing through an isothermal high density region is analysed. The criteria for the stability of jets due to the formation of internal shocks are discussed.

1. Introduction

The standard model for Fanaroff-Riley type II radio sources is described as a pair of relativistic jets of electrons which is ejected in opposite directions from a very compact region in the nucleus of an elliptical galaxy (Blandford 1990). The jets expand adiabatically through the interstellar medium of the host galaxy and the surrounding intergalactic medium. Collimation of the jets is provided by the presence of a cavity or "cocoon" surrounding the jet, which maintains the pressure of the intergalactic medium in balance with that of the relativistic gas within the jet. In this model, the jets maintain a straight trajectory. However, observations have shown that jets often bent.

Typical examples of bending in radio sources appear in *radio trail* sources, *mirror symmetric* sources and radio galaxies which present *inversion symmetry* (Begelman, Blandford, & Rees 1984). Another way of inducing deflections in radio jets is if the beam passes through a region of interstellar or intergalactic gas in which there is a significant pressure gradient. This can occur if the jets pass through the interstellar medium of a large galaxy or diffuse intergalactic cloud. Observations of this might be present in the radio galaxy 3C31 (Best, Longair, & Röttgering 1997), but the quasar PKS 1318 + 113 (Lehnert, et al.) is an extremely good evidence of a deflection induced by a jet–cloud interaction.

2. Jet–cloud interactions

The interaction of an astrophysical jet with a cloud, in which the characteristic size of the cloud is much greater than the jet radius, has been studied in its initial stages by Raga & Cantó (1995). Their results show that initially the jet slowly begins to bore a passage into the cloud. Eventually a stationary situation is achieved in which the jet penetrates the cloud and escapes from it in a direction which is different from the original jet trajectory.

Once the steady state in this interaction is reached, the trajectory is determined by maintaining pressure equilibrium with the surrounding environment. Since the expansion of the jet is adiabatic and a steady state has been reached, Bernoulli's equation in its relativistic and non–relativistic form (Landau & Lifshitz 1987) can be used to describe the path of the jet (Mendoza, & Longair 2000).

With all these considerations, once the distribution of the gas inside the cloud is known, it is possible to integrate Bernoulli's equation numerically with the use of a Runge–Kutta method. Analitic solutions are possible for the case in which the jet penetrates the cloud at a position $\mathbf{r}_0$ with a high supersonic motion (Mendoza, & Longair 2000).

Let us first discuss the case in which the cloud is an isothermal sphere for which it's density, and hence its pressure, is inversely proportional to the square of the radius vector. Under these circumstances, the problem is characterised by the gravitational constant G, a "characteristic length" r_0 and the values of the velocity of the jet and the density at this point which are v_0 and ρ_0 respectively. Three independent dimensions (length, time and mass) describe the whole hydrodynamical problem. Since four independent physical quantities (G, ρ_0, v_0, and r_0) are fundamental for the problem we are interested, the Buckingham Π–Theorem (Sedov 1993) of dimensional analysis demands the existence of only one dimensionless parameter $\Lambda \equiv G\rho_0 r_0^2/v_0^2$. This parameter is obtained naturally from the full analytic solution (Mendoza, & Longair 2000). The other obvious dimensionless number that parametrises the solutions is the Mach number M_0 evaluated at position r_0.

The deflection of non–relativitic jets in isothermal clouds might be important for interstellar molecular clouds and the jets associated with Herbig–Haro objects. If we adopt a particle number density of $n_{\mathrm{H}} \sim 10^2\,\mathrm{cm}^{-3}$, and a temperature $T \sim 10\,\mathrm{K}$ for a cloud with radius $r_0 \sim 1\,\mathrm{pc}$ (Spitzer 1998), (Hartmann 1998), then $\Lambda \sim 10^{-2}/M_0^2$. The same calculation can be made for the cases of radio jets interacting with the gas inside a cluster of galaxies. For this case, typical values are $n_{\mathrm{H}} \sim 10^{-2}\,\mathrm{cm}^{-3}$, $T \sim 10^7\,\mathrm{K}$ and $r_0 \sim 100\,\mathrm{Kpc}$ (Longair 1992, Longair 1998). With these values, the parameter $\Lambda \sim 10^{-2}/M_0^2$, which is the same value as the one obtained for Herbig–Haro objects. The fact that jets are formed in various environments such as giant molecular clouds and the gaseous haloes of clusters of galaxies with the same values of the dimensionless parameter Λ provides a clue as to why the jets look the same in such widely different environments.

From its definition, the parameter Λ can be rewritten as $\Lambda = (3/4\pi) \times (G\mathsf{M}/r)(1/v_0^2)$, where M is the mass within a sphere of radius r_0. This quantity is roughly the ratio of the gravitational potential energy from the cloud acting on a fluid element of the jet, to its kinetic energy at the initial position r_0. The parameter Λ is thus an indicator of how large the deflections due to gravity are going to affect the trajectory of the jet. The bigger the number Λ, the more important the deflection caused by gravity will be. In other words, when the parameter $\Lambda \gg 1$ the jet becomes ballistic and bends towards the centre of the cloud. When $\Lambda \ll 1$ the deflections are dominated by the pressure gradients in the cloud and the jets bend away from the centre of the cloud.

Let us consider next the case of a galaxy dominated by a dark matter halo for which the mass density is given by the relation (Binney & Tremaine 1987): $\rho_d = \rho_{d\star} / \left(1 + (r/a)^2\right)$, in which a is the core radius and quantities with a star refer to the value at the centre of the galaxy. The gas in the galaxy is in hydrostatic equilibrium with the dark matter halo, so that $\mathbf{grad}\, p = -\rho\, \mathbf{grad}\, \phi_d$. In exactly the same form as it was done above, the important parameters in the problem are the gravitational constant G, the characteristic length a and the sound speed $c_\star$, together with the gas density $\rho_\star$ evaluated at the centre of the cloud. Since three independent dimensions (length, time and mass) describe the whole hydrodynamical problem, dimensional analysis demands the existence of only one dimensionless parameter $k \equiv -4\pi G \rho_{\mathrm{d}_\star} a^2 / c_\star^2$. The unimportant proportionality factor of -4π is introduced here since it appears naturally in the analytic solution (Mendoza, & Longair 2000). The Mach number M_0, evaluated at the point where the jet enters the cloud is another dimensionless number which parametrises the solution of this problem. Using typical values (Binney & Tremaine 1987) for galaxies then $\rho_\star \sim 0.1\, M_\odot\, \mathrm{pc}^{-3}$, $\mathsf{a} \sim 1\, \mathrm{Kpc}$. Taking central values for the gas in the galaxy as $n_\star \sim 1 \mathrm{cm}^{-3}$ and $T_\star \sim 10^5 \mathrm{K}$ then $k \sim -10$.

The number k can be rewritten as $k = -\left(4/(4-\pi)\right)(G\mathsf{M}/\mathsf{a})(1/c_\star^2)$, where M is the mass of a sphere with radius a. This quantity is proportional to the gravitational energy of the cloud evaluated at the core radius divided by the sonic kinetic energy that a fluid element in the jet has. In other words, in the same way as it was done above, the dimensionless number k is an indicator as to how big deflections produced by gravity are.

Consider now the case in which relativistic effects are included in the interaction of a relativistic jet and a stratified high density region. To simplify the problem, the self gravity of the cloud acting on the jet is ignored. Bernoulli's equation in its non–relativistic form can be integrated numerically under this considerations and it is possible to find out analytic solutions when the Mach number of the flow inside the jet is much greater than unity. This was done for the case in which the cloud is an isothermal sphere and for the case in which the interaction is between the jet and gas in pressure equilibrium with a dark matter halo (Mendoza, & Longair 2000).

3. Discussion

When a jet bends it is in direct contact with its surroundings and entrainment from the external gas might cause disruption to its structure (Icke 1991). However, if this situation is bypassed for example by an efficient cooling, then there remains a high Mach number collimated flow inside a curved jet. When supersonic flow bends, the characteristics emanating from it intersect at a certain point in space (Landau & Lifshitz 1987). Since the hydrodynamical values of the flow in a characteristic line have constant values, the intersection causes the different values of these quantities to be multivalued. This situation can not occur in nature and a shock wave is formed.

The formation of internal shocks inside the jet gives rise to subsonic flow inside it and collimation may no longer be achieved. If the characteristic lines produced by the flow inside the jet intersect outside it, then a shock wave is not formed and the jet remains collimated as it bends. However, two important points have to be considered in the discussion. The first is that the Mach number decreases in a bend as the flow moves. The second is that the rate of change of the Mach angle with respect to the angle the jet makes with its original straight trajectory (the bending angle) increases without bound as the velocity of the flow tends to that of the local velocity of sound. This was first proved by Icke (1991) for the case in which no relativistic effects were taken into account. We have made a relativistic generalisation to these two points (Mendoza 2000).

The fact that two shocks might form inside a jet, one of them at the end of the bending when the Mach number is near one, enables us to find an upper limit to the bending angle (Icke 1991). For example, a non–relativitic jet with a polytropic index $\kappa = 5/3$ cannot be deflected more than $60.8°$. Under the same non–relativitic conditions, but by assuming a polytropic index $\kappa = 4/3$, non–relativitic jets with a relativistic equation of state cannot be deflected more than $148.12°$ (Icke 1991).

When a full relativistic analysis is introduced in this description, this upper limit can not be greater than its non–relativitic counterpart. This is because characteristic lines emanating from a relativistic flow are closer to the streamlines as compared to their non–relativitic counterparts (Königl 1980). As a result, a relativistic jet with a polytropic index $\kappa = 4/3$ can not bend more than $47.94°$. The precise conditions under which an internal shock is produced for a given jet depend on the shape of the curve that the jet makes as it bends and the radius of the jet.

The most important consequence of the calculations described above is the sensitivity of the deflection angles to variations in velocity. This sensitivity is due to the fact that the force applied to a given fluid element in the jet (due to pressure and gravitational potential gradients) is the same independent of the velocity of the flow in the jet. However, as the velocity of the flow in the jet increases, there is not enough time for this force to change the curvature of the jet soon enough, giving rise to very straight jets.

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